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The purpose of the present investigation was to develop physiological limit criteria for cold weather clothing items which meet the limits for protection against development of a cold injury, and which are also associated with an increased level of subjective comfort and acceptance. The literature on physiological responses to cold was reviewed. The relationships of responses such as body core temperature, skin temperatures and shivering to subjective feelings of thermal comfort and temperature sensation were examined. Under many conditions that Navy cold weather clothing items are worn, it is not practical to expect that the optimal level of thermal comfort can be obtained. Allowing for a moderate level of cold sensation and thermal discomfort, the following physiological criteria for acceptance of cold weather clothing items were developed: 1) a mean weighted skin temperature $\geq$ 28°C (82°F) 2) local skin temperature at any site $\geq$ 18°C (64°F) 3) a metabolic rate due to shivering < twice the normal resting rate (metabolic rate $\leq$ approximately 180 kcal/hr). All three criteria must be met. Application of these criteria will enable us to better evaluate and compare cold weather clothing items.

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PHYSIOLOGICAL ACCEPTANCE CRITERIA FOR COLD WEATHER CLOTHING

Background. When our laboratory evaluates the thermal protection of cold weather clothing items, the items are considered acceptable if they protect the wearer from cold injuries. Body temperature limits have been established which are used to greatly reduce the risk of whole body and local cold injuries. The limit that is used for the prevention of whole body overcooling, or hypothermia, is a core temperature of 35°C (95°F). (Clinical hypothermia is usually associated with a core temperature of 33°C.) For prevention of a local cold injury such as frostnip or frostbite, a skin temperature limit of 5°C (40°F) at any site is used. Typically, these "pass/fail" criteria are applied when the garment is worn for a pre-determined time period, such as 2 hours during cold water immersion, or 3 hours during a simulated watch duty in cold air.

In our laboratory evaluations of cold weather clothing, a number of garments are usually compared to each other and/or to the standard item currently in use. The experimental garments may include different fabrics, fabric combinations, or designs. Often, a number of the garments being tested meet the criteria described above for prevention of cold injury. The garments may then be ranked according to differences in level of physiological strain that each induces. A decreased physiological strain is usually associated with increased thermal comfort and user acceptance. Decreased strain may also be associated with improved cognitive performance and manual dexterity.

The purpose of the present investigation was to develop physiological limit acceptance criteria for cold weather clothing items which, in addition to meeting the limits for protection against cold injury, are associated with an increased level of subjective comfort and acceptance. The acceptance criteria are based specifically on clothing worn in a cold air, rather than a cold water environment. Application of these criteria will enable us to better evaluate and compare cold weather clothing items.

Approach. The literature on physiological responses to cold was reviewed. The relationships of physiological responses such as core temperature, skin temperatures, and shivering to subjective feelings of thermal comfort and temperature sensation were examined. Physiological and subjective data from several cold weather evaluations conducted at the Navy Clothing and Textile Research Facility (NCTRF) were also examined.

Thermal sensation and thermal comfort. Although some studies have used rating scales which combine feelings of thermal comfort and thermal sensation, the two responses can be differentiated. Thermal comfort is described by feelings of comfort/discomfort, or pleasantness/ unpleasantness. Rating scales of thermal comfort typically include verbal anchors ranging from comfortable to extremely uncomfortable. Thermal sensation is described by feelings of warmth or cold. Scales of thermal sensation usually include 7-9 numerical ratings with verbal anchors ranging from "very hot" to "neutral" to "very cold". Examples of the two types of scales are shown in Table I.

Table I. Comfort and temperature sensation scales (10).

Comfort Sensation	Thermal Sensation
1 Comfortable	1 Cold
2 Slightly uncomfortable	2 Cool
3 Uncomfortable	3 Slightly cool
4 Very uncomfortable	4 Neutral
	5 Slightly warm
	6 Warm
	7 Hot

Depending on the conditions, a particular rating on one scale may be associated with different ratings on the other scale. For example, a comfort rating of "comfortable" may be combined with a temperature rating of "neutral" in some cases, "slightly cool" in the summer, or "slightly warm" in the winter.

In the heat, temperature sensation and thermal comfort are primarily due to central thermoreception, or an increased core temperature (2, 11). Despite high skin temperatures during exposure to hot environments, as long as core temperature is not significantly elevated, individuals may remain thermally comfortable. In the cold, however, temperature sensation is less dependent on central, and more dependent on peripheral input, or skin thermoreception (2, 11). In his pioneer work in 1927 on thermal comfort, Yaglou reported the correlation between thermal comfort and skin temperature (32). Since that time, a large number of studies have further demonstrated the relationship between skin temperature and feelings of

thermal discomfort and cold sensation (2-4, 7, 9-12, 14, 15, 18, 21, 22, 24, 31, 34). The following sections describe the role of absolute skin temperature on thermal sensation and several factors which modify the effect of skin temperature, such as homogeneity, level of activity, rate and direction of change, and shivering.

Skin temperature. The best single index of cold sensation and thermal comfort has been shown to be skin temperature. In warm environments, the average skin temperature for optimal thermal comfort is approximately 33-34°C (91-93°F) (10, 12, 14, 18, 22-24, 31, 32). Below a mean skin temperature of 33°C, discomfort begins, and the relationship between temperature and thermal sensation follows a linear pattern throughout a wide range (3, 5, 10, 15, 19, 21, 31). Approximate mean skin temperatures and their corresponding thermal sensations are: 33°C = "neutral", 29°C = "cool", 27°C = "cold", 25°C = "very cold", and 23°C = "unbearably cold". The maximum intensity of cold sensation is experienced at a mean skin temperature of approximately 20°C (2). Below this level, the linear relationship between absolute temperature and temperature sensation does not continue. One study showed that at mean skin temperatures of 18°C and 13°C, there was no difference in the sensation of cold (11). The sensation of discomfort, however, continued to increase.

Effect of exercise on skin temperature for comfort. As activity level increases, the mean skin temperature for comfort has been shown to decrease (3, 8, 11, 17, 23, 29, 33). Fanger describes this relationship mathematically as: $t_s = 35.7 - 0.032(H/A_D)$, where t_s = mean skin temperature ($^{\circ}$C), H = internal heat production of the body (kcal/hr),

and A_D = body surface area (m^2) (6, 8). Using this equation, a comfortable mean skin temperature at rest (H = 90 kcal/hr) is 34°C. At an activity level of 270 kcal/hr, comfortable mean skin temperature is 31°C. This corresponds to a decrease in skin temperature for comfort of approximately 1.6°C per MET (1 MET is equivalent to the oxygen consumption at rest). Other researchers have shown a decrease in comfortable skin temperature of approximately 2°C per MET (11, 17, 23). In his Antarctica study, Budd reported that at mean skin temperatures below 28°C, subjects tended to feel comfortable during heavy work but too cold during light work (3).

Effect of clothing. Several studies have examined the effect of clothing on skin temperature for comfort (20, 23, 30). These authors have compared preferable skin temperatures for subjects that were nude and wearing different types of clothing. They have concluded that skin temperature for comfort is independent of the clothing worn.

Effect of uniformity of skin temperature and local skin temperature. In the heat, local skin temperatures measured at various sites on the body are fairly uniform. In the cold, however, large differences in surface temperatures can occur on the different body parts. The trunk is usually the warmest area, followed by the arms and legs, hands and then feet. The uniformity of skin temperature over the body surface has been shown to affect subjective ratings of thermal comfort (15, 20). As the skin temperature becomes more non-uniform, discomfort increases.

The absolute skin temperature levels for discomfort and cold sensation vary for different body surfaces. In general, overall mean skin temperature transitions from "neutral" to "cool" at approximately 31°C, and discomfort begins. For the hand, however, a temperature of 26°C is described as "neutral" (compared to 33°C for mean skin temperature), and 20°C is described as "cold" (compared to 27°C for mean skin temperature) (5). Cold sensation and discomfort for the fingers and toes are experienced at even lower absolute temperatures. Discomfort for the finger generally begins at a temperature of 20°C and for the toe at a temperature of 17°C (13). At some point below approximately 18°C, local skin temperatures, even over very small areas, begin to transition from discomfort to pain (15). For the hand, several authors have reported that pain occurs at temperatures below 16°C (4, 5).

Figure 1 illustrates how subjective ratings of temperature sensation may vary depending on which part of the body is being rated. These data are from an evaluation of Navy extreme cold weather clothing during which eight subjects were seated for 2 hours in an ambient condition of 0°C (32°F) with a 2.2 m/s (5 mph) wind (27). Skin temperatures were measured at ten sites. Subjects were periodically asked to give individual ratings of thermal sensation for the various body parts as well as for an overall rating. As shown in Figure 1, the mean weighted skin temperature associated with an overall thermal sensation rating of "cool" was 28°C. A rating of "cool" for the hand, however, was reported at a finger temperature of 20°C. When toe temperature was 13°C the thermal rating for the foot was only "cool to cold", even though a mean skin temperature of 23°C is usually considered "unbearably cold".

Rate and direction of change in skin temperature. The relationship between skin temperature, temperature sensation and thermal comfort can be altered if skin temperature is changing. Both the rate and the direction of change have been shown to alter subjective responses normally associated with absolute skin temperature levels (10, 11, 14, 16, 28). After exposure to cold, a rapid increase in skin temperature will be sensed as "comfortable", even when absolute skin temperature is well below that point normally associated with comfort. Even at slower rates of change, a mean skin temperature in a cold environment may be described as comfortable if it is rising, but uncomfortable if it is falling (11, 14).

Figures 2 and 3 illustrate the effect of activity level and direction of change of skin temperature on subjective ratings of thermal sensation. The data are from two cold weather clothing evaluations (25, 26) conducted at NCTRF. In both evaluations, the thermal protection of different types of cold weather protective ensembles were compared when worn by subjects for 3 hours in a cold environment. During the first and third hours, the subjects remained seated at rest. During the second hour, they walked on a level treadmill at 1.6 m/s (3.5 mph). Figure 2 shows the average mean weighted skin temperature response (based on measurements at ten sites) of eight subjects. In this evaluation, an intermediate cold weather jacket and trouser ensemble was worn over the Navy utility uniform in a -7°C (20°F) environment. Figure 3 is the average of seven subjects who wore two different extreme cold weather coveralls in a -18°C (0°F) environment. In both figures, a skin temperature of approximately 28°C (82°F) is described as "cool" when temperature is dropping (during rest) and as "neutral" when temperature is rising (during exercise).

Shivering. Down to a mean skin temperature of approximately 30°C, metabolic rate at rest is fairly constant (35). Below this level, shivering occurs, which can double or triple the resting metabolic rate (2, 8, 10). While not necessarily perceived as a sensation of cold, shivering has been shown to be associated with discomfort and is considered to be a disagreeable state (1, 4).

Physiological acceptance criteria. The research has shown that skin temperature is the best single indicator of thermal comfort and thermal sensation. For resting individuals, thermal discomfort from the cold begins at mean skin temperatures below 33°C (91°F). Decrements in cognitive performance due to the cold have been reported starting at mean skin temperatures below 30°C (13). It is not practical to expect that Navy cold weather clothing should provide this optimal level of comfort or performance. Allowance for some degree of cold sensation and thermal discomfort should be made. It may be expected that a level of thermal comfort between "slightly uncomfortable" and "uncomfortable", and a level of thermal sensation between "cool" and "cold" be obtained. The mean weighted skin temperature associated with these levels (at rest) is approximately 28°C, or 82°F (3, 5, 10, 11, 15, 19, 21, 31). These apply for rest; in cold air, it is easy to maintain skin temperature above 28°C when exercise is done. When applying a mean skin temperature limit of 28°C, the condition of relative uniformity of skin temperature must

also be met. If any local skin temperature deviates too far from the mean value, the level of thermal discomfort will be affected. A practical limit for our purposes would be a maximum deviation of 10°C from the mean skin temperature for any local skin temperature. Assuming a mean skin temperature limit of 28°C, this would limit local skin temperatures to an absolute value of 18°C (64°F). This represents approximately the point where discomfort for the hands and feet begin, but above the level associated with decreased dexterity (5, 13).

In addition to skin temperature, shivering is perceived as an important determinant to the sense of discomfort in the cold. Therefore, acceptance of cold weather clothing items should also incorporate a limit based on the level of shivering that occurs when the garment is worn. At a mean skin temperature of 28°C (one of our acceptable criteria), shivering increases the metabolic rate over resting values by approximately 1.6 times (2). The amount of shivering at a given skin temperature, however, varies among individuals (as do levels of comfort and thermal sensation). Therefore, it would be reasonable to accept cold weather clothing items if, in addition to a mean skin temperature criterion of ≥28°C, they induce a metabolic rate that is less than twice the normal resting rate.

Summary. The relations between various physiological responses to subjective sensations of temperature and thermal comfort were examined. If we allow for a moderate level of cold sensation and subjective discomfort, the following "pass" physiological criteria for acceptance of cold weather clothing items can be applied:

1) a mean weighted skin temperature $\geq 28^{o}C$ ($82^{o}F$)
2) local skin temperature at any site $\geq 18^{o}C$ ($64^{o}F$)
3) a metabolic rate due to shivering < twice the normal resting rate (metabolic rate $\leq$ approximately 180 kcal/hr)

All three criteria must be met. In some extreme environments, particularly during cold water immersion, these criteria may not be met. However, these are not considered conditions where comfort can be obtained. Rather, they are survival situations where a great deal of discomfort can be expected. In these cases, none of the garments being evaluated may be able to pass the physiological criteria above. However, the garments may still be able to be compared in terms of acceptability for cold weather use. As stated eariler, the degree of cold and discomfort sensation decreases linearly as skin temperature decreases, throughout a wide range of skin temperatures. Therefore, the garment which maintains skin temperature at the highest absolute level may be the best choice.

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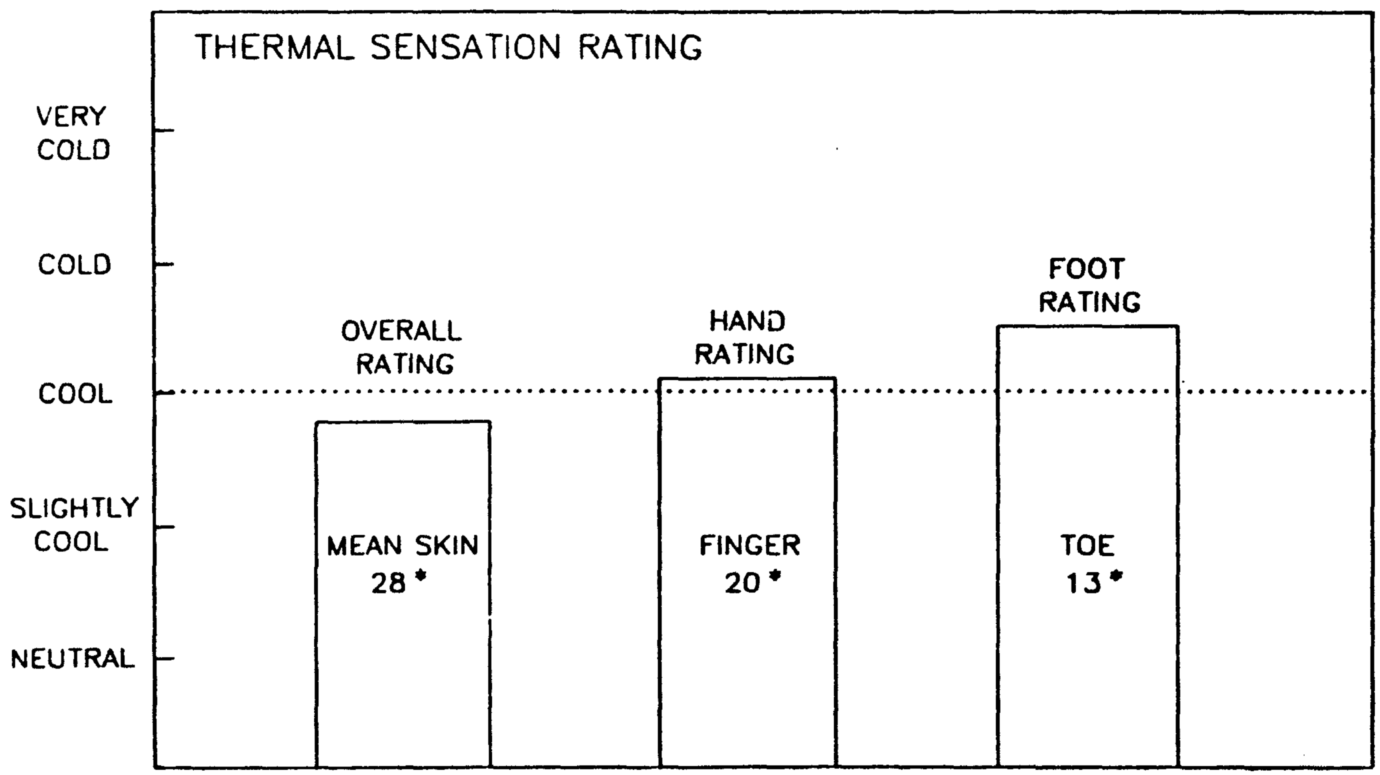
Appendix A. Illustrations

AMBIENT 0°C, 2.2 m/s wind

Extreme Cold Weather Clothing

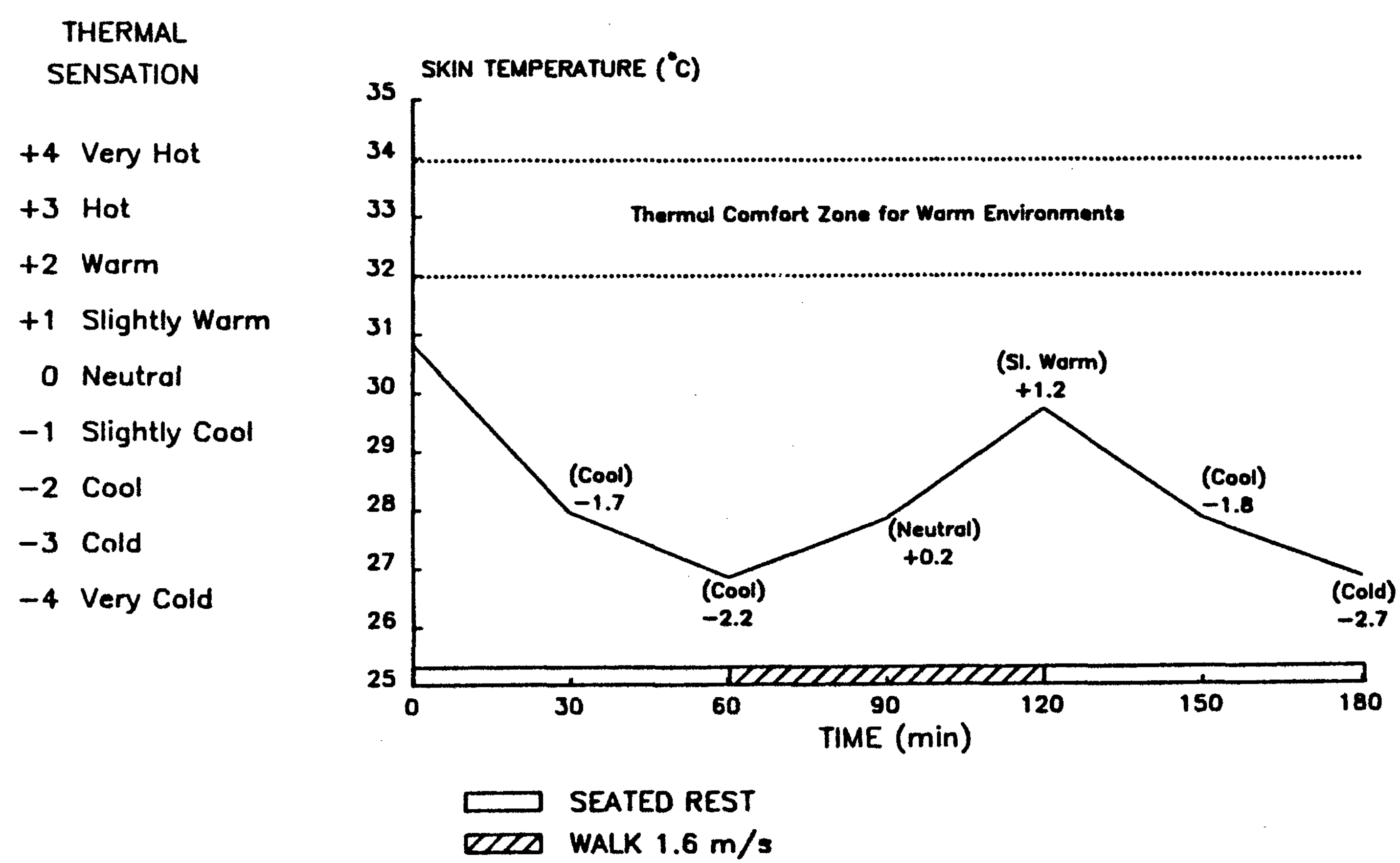


*Temperature (°C) after 60 min of seated rest

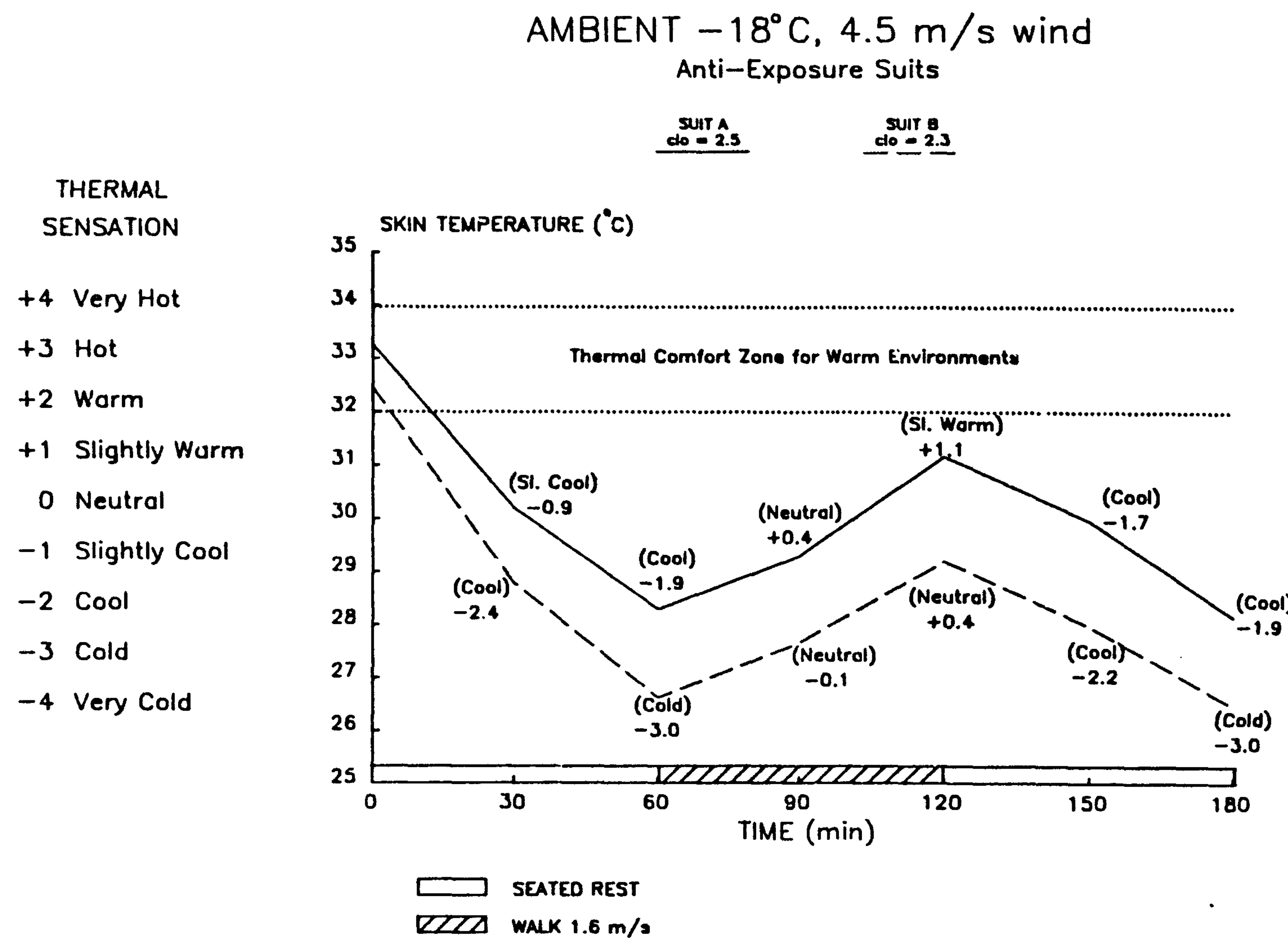
A-2 (Figure 1)

AMBIENT −7°C, 2.0 m/s wind

Intermediate Cold Weather Clothing



A-3 (Figure 2)


AMBIENT −18°C, 4.5 m/s wind
Anti–Exposure Suits
SUIT A
clo = 2.5
SUIT B
clo = 2.3
THERMAL
SENSATION
+4 Very Hot
+3 Hot
+2 Warm
+1 Slightly Warm
0 Neutral
−1 Slightly Cool
−2 Cool
−3 Cold
−4 Very Cold
SKIN TEMPERATURE (°C)
35
34
33
32
31
30
29
28
27
26
25
Thermal Comfort Zone for Warm Environments
(Sl. Cool)
−0.9
(Cool)
−1.9
(Neutral)
+0.4
(Sl. Warm)
+1.1
(Cool)
−1.7
(Cool)
−1.9
(Cool)
−2.4
(Cold)
−3.0
(Neutral)
−0.1
(Neutral)
+0.4
(Cool)
−2.2
(Cold)
−3.0
0
30
60
90
120
150
180
TIME (min)
SEATED REST
WALK 1.6 m/s